

1.3 Harvesting Chemical Energy



Which device—the snowmobile or the camera phone—is powered by fossil fuels? The snowmobile’s internal combustion engine runs on gasoline, a petroleum product. As you learned in the previous lesson, petroleum is a valuable fossil fuel. But what is the energy source for a camera phone? These phones run on rechargeable batteries that must be periodically plugged into a wall outlet for recharging. The number of devices like camera phones that run on rechargeable batteries demonstrates the importance of electricity in society. In Alberta, coal—a fossil fuel—is used to generate over 75% of the electricity. So, like almost every other device that runs on rechargeable batteries in Alberta, the camera phone is also powered by a fossil fuel.

Are you surprised that both of these devices are fossil-fueled? Most people in Alberta don’t make the connection between electricity and fossil fuels. As you covered in Lesson 1.2, fossil fuels are non-renewable. Even though supplies of fossil fuels are being depleted, you have learned that the rate at which they are being used as an energy source is actually increasing. In this lesson you will investigate what makes fossil fuels so energy-rich, how the energy content of fuels is determined, and how the energy from fossil fuels is released and converted into other forms of energy.



DID YOU KNOW?



In 2006, over 2000 tonnes of rechargeable batteries were discarded in Canada. Rechargeable batteries can contain metals like nickel, cadmium, aluminium, and cobalt, all of which can be toxic to organisms within the environment. Many areas have programs to promote the proper disposal of rechargeable and non-rechargeable batteries to help prevent metals from leaching into water and soil.

Energy Released in Combustion Reactions

Releasing the stored energy in gasoline or coal involves **combustion**. Recall that combustion is a type of chemical reaction that requires oxygen and, in the case of hydrocarbons, yields carbon dioxide and water vapour. During a combustion reaction, the chemical bonds within the fuel are broken and new chemical bonds are formed. The process of breaking and forming chemical bonds results in a change of chemical potential energy. Hydrocarbons are considered to be energy-rich molecules. The chemical potential energy of a hydrocarbon is the sum of the potential energy stored in all of the bonds in the molecule.

combustion: a chemical reaction that occurs in the presence of oxygen and results in the release of energy

Combustion of Octane

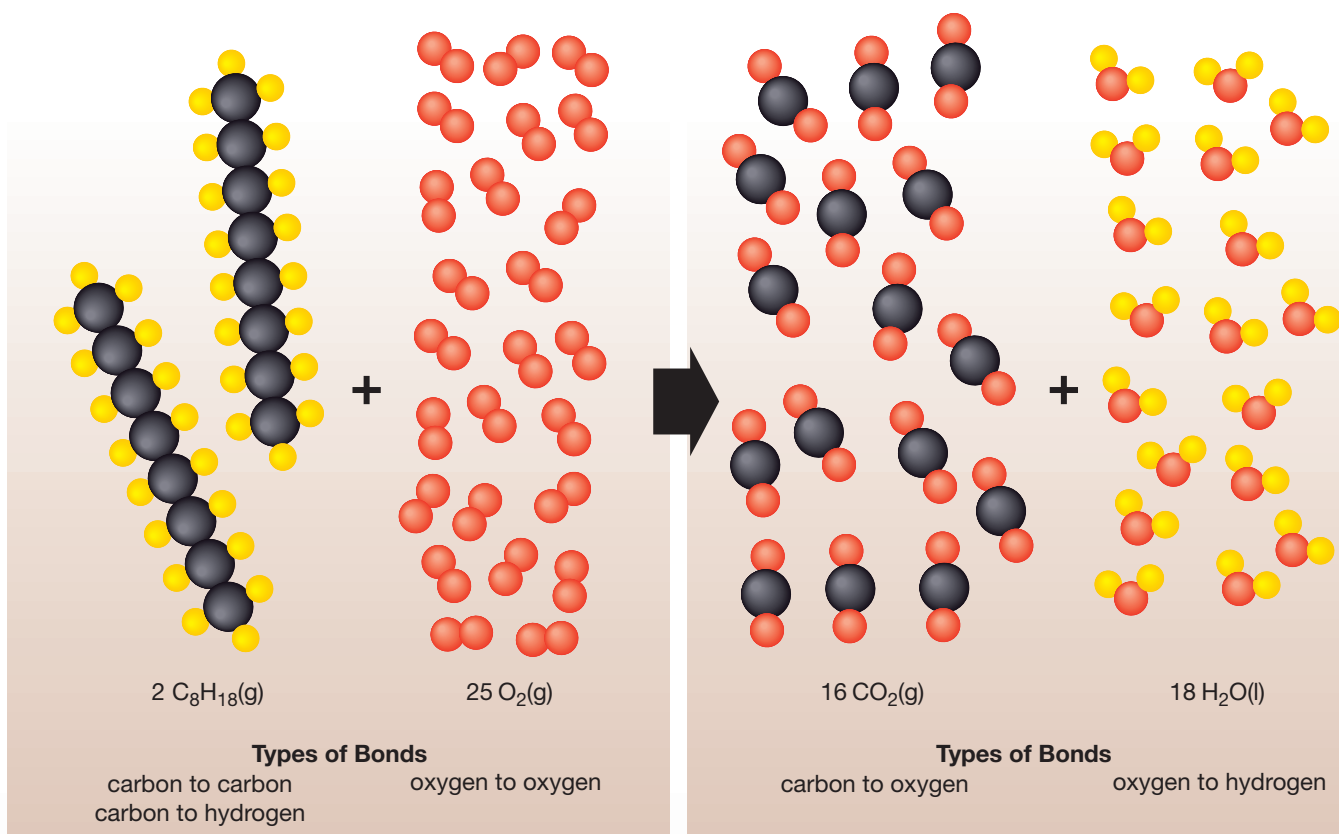


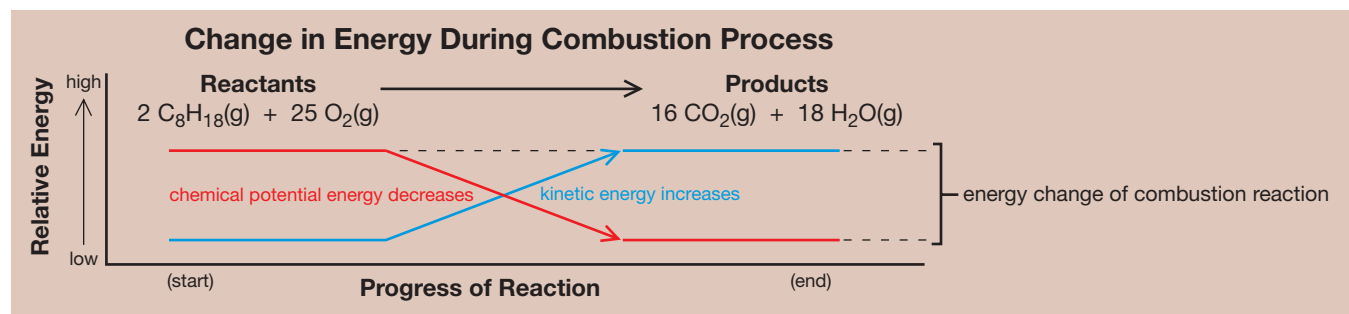
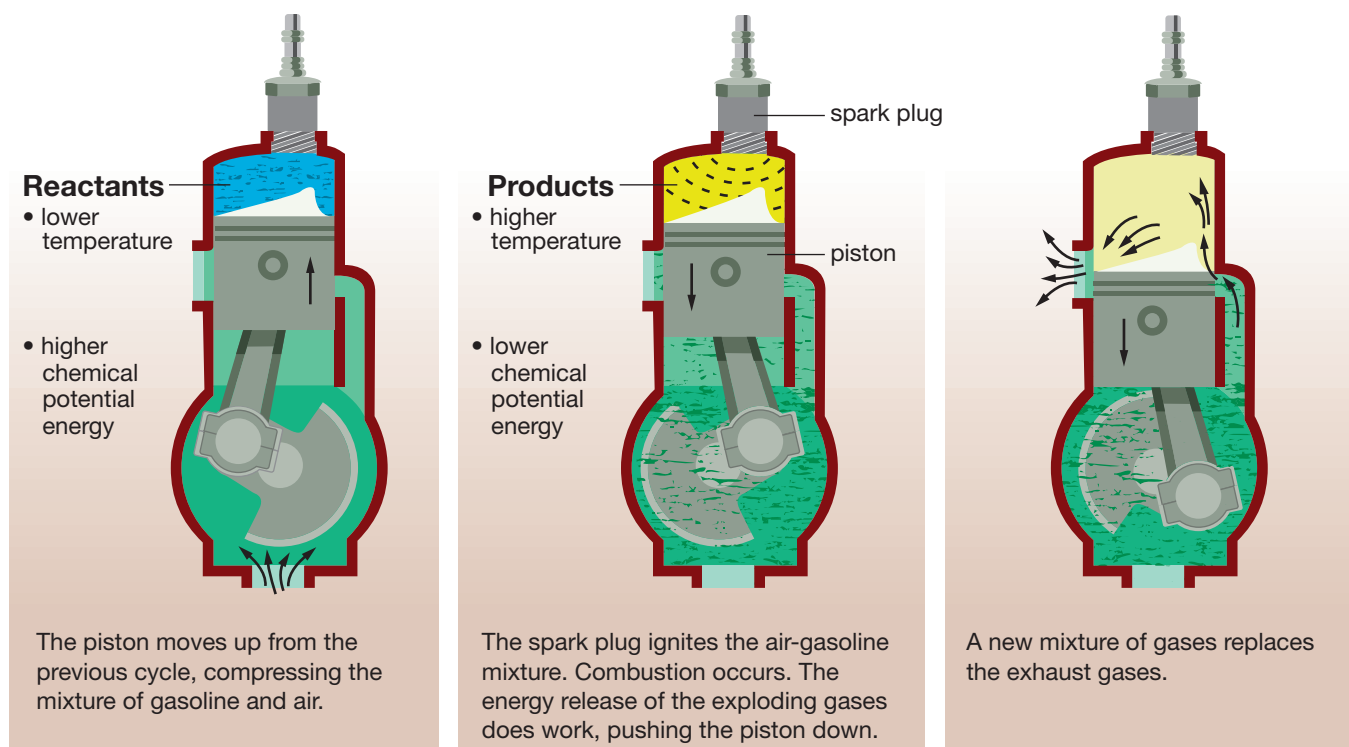
Figure D1.27: The combustion of octane, a component of gasoline, involves breaking chemical bonds and forming new chemical bonds between atoms.



- **temperature:** a measure of the average kinetic energy of the atoms or molecules of a substance
- **heat:** the transfer of energy from molecules or atoms at a higher temperature to those at a lower temperature

The release of energy that occurs as a result of a combustion reaction can take many forms. Radiant energy in the form of infrared and visible light photons is emitted from the flame produced by the reaction. During a combustion reaction, the kinetic energy of the molecules involved also changes. The products of a combustion reaction are at a higher **temperature** than the reactant molecules. Recall that the collision between molecules with different kinetic energies results in a transfer of energy from warmer to cooler objects—this is often called a transfer of **heat**. The following illustration shows the energy changes that occur during the operation of a snowmobile engine:

Combustion in a Typical Snowmobile Engine



It is important to remember that not all of the energy released by the combustion of a fossil fuel does useful work on the moving parts of the engine. The radiant energy from the spark does not contribute to the useful work of pushing the piston down, nor does the energy that transfers to the non-moving parts of the engine. Earlier, you learned that energy efficiency is defined as the proportion of input energy that is converted into useful output energy.

Practice

20. Identify the forms of the input energy and output energy associated with the operation of a snowmobile engine.
21. Rewrite the formula for energy efficiency to reflect the forms of energy involved in operating a combustion engine like one found in a snowmobile.

Heat of Combustion

The rearrangement of atoms that occurs during a chemical reaction results in a change of potential energy. When the chemical reaction involves combustion, the product molecules store less chemical potential energy in their bonds relative to the bonds between the atoms of the reactant molecules. The difference in the potential energies of the reactants and products corresponds to the energy released during the combustion reaction. Figure D1.28, an energy diagram, summarizes the energy change that occurs during a combustion reaction.

The symbol $\Delta_c H^\circ$, the **heat of combustion**, is used to represent the quantity of energy released during the combustion reaction. As shown in Figure D1.28, the molecules in the products have a lower potential energy than the molecules in the reactants. This means a release of energy in this combustion reaction occurred. Chemical changes that involve a release of energy are called **exothermic changes**. As you will see later, an exothermic energy change can be represented using a negative sign to signify that energy is released by the process to the surroundings.

In Lesson 1.2 you compared the energy densities of wood, charcoal, and coal. The energy densities you compared express the heat of combustion for each of these fuels per gram of fuel combusted. In the next investigation you will have an opportunity to perform an experiment to determine the heats of combustion and energy densities of some fuels.

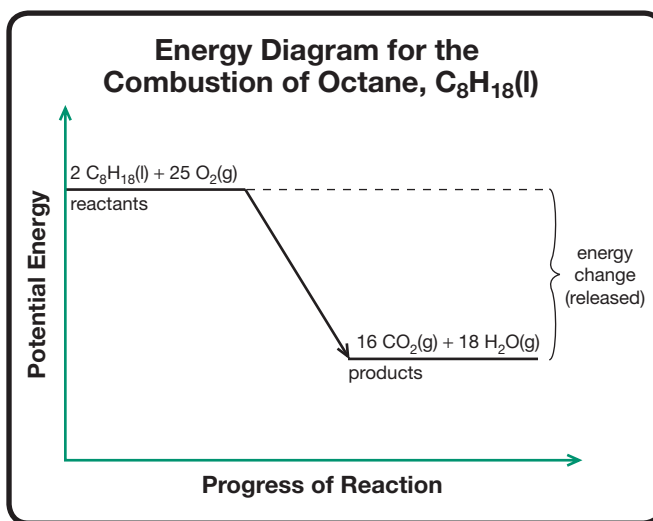


Figure D1.28

- ▶ **heat of combustion ($\Delta_c H^\circ$):** the amount of heat released when a substance undergoes combustion
- ▶ **exothermic change:** a chemical change that involves a release of energy, usually in the form of heat, to the surroundings

Investigation

Determining Heat of Combustion

Purpose

You will determine and compare the amount of heat released by the combustion of three different fuels.

Experimental Design

During the experiment you will measure the mass of each fuel required to raise the temperature of 20.0 mL of water 20.0°C. The data you collect will be used to calculate an experimental value for the heat of combustion of each fuel tested.



Science Skills

- ✓ Performing and Recording
- ✓ Analyzing and Interpreting



CAUTION!

Because you will be working with open flames in this investigation, ensure that you and your partners take the following precautions:

- Wear safety goggles.
- Avoid wearing loose clothing.
- Tie back long hair.
- Keep your workspace clear of combustible materials.
- Be aware of the procedures for safely dealing with fire in the laboratory.



Materials

- graduated cylinder
- electronic balance
- test tube clamp
- matches
- test tube rack
- thermometer
- candle holder
- ethanol burner
- 3, 25 mm by 200 mm test tubes
- 60 mL of distilled water at room temperature
- thermometer clamp
- 100% paraffin wax candle
- eyedropper
- laboratory stand
- butane lighter
- “Determining Heat of Combustion” handout from the Science 30 Textbook CD



Procedure

- step 1:** Use a graduated cylinder to fill each of the three test tubes with 20.0 mL of distilled water. Once you have filled the test tubes, place them in a test tube rack for later.
- step 2:** Use the electronic balance to measure the initial masses of each of the following: ethanol burner with ethanol inside, butane lighter, and candle plus candle holder. Record these values in the data table given in the handout.
- step 3:** Assemble the apparatus as shown in the handout. The bulb of the thermometer should not be touching the bottom or walls of the test tube. Measure the initial temperature of the water in the first test tube, and record it in the data table.
- step 4:** Determine the desired final temperature by adding 20.0°C to the initial temperature, and record it in the data table.
- step 5:** Ignite the ethanol burner, and quickly place it under the test tube so that the upper tip of the flame just touches the bottom of the test tube. Carefully monitor the rising temperature of the water. Once it reaches the final desired temperature, quickly remove the ethanol burner and extinguish the flame.
- step 6:** Replace the first test tube with another test tube from the test tube rack, and repeat steps 4 and 5 with the butane lighter.
- step 7:** Replace the test tube with the last test tube in the rack, and repeat steps 4 and 5 to test the paraffin (candle) wax.
- step 8:** Use the electronic balance to measure the final masses of each of the following: the alcohol burner containing the ethanol, the lighter containing the butane, and the candle. Record these values in the data table given in the handout.
- step 9:** Disassemble and clean the apparatus, and return all materials to their appropriate places. Make sure your work area is also clean.


Analysis

1. Complete the table in the Analysis part of the “Determining the Heat of Combustion” handout.
2. Identify the manipulated and responding variables in this experiment.
3. List three variables that were controlled during this experiment. Describe the actions you took to maintain consistency between trials.
4. Since the energy change for each trial was identical, use the mass of fuel combusted to rank the three fuels from most energetic to least energetic.
5. Use the calculated values for heat of combustion from your table to rank the fuels from highest heat of combustion per mole to the lowest.
6. Describe the relationship between the molar mass of the molecule tested and the heat of combustion per mole of each fuel tested.
7. Compare the rankings listed in your answers to questions 4 and 5. Account for any differences between the two answers.
8. Identify one major flaw in the design of this experiment. Hypothesize how this flaw may have affected your results.
9. Suggest improvements to the apparatus that might minimize the flaw indicated in question 8. If possible, include a diagram of your improvements to the apparatus used in the experiment.

Calorimetry—Measuring Energy Changes



A **calorimeter**, like the one you constructed and used in the “Determining Heat of Combustion” investigation, is a device that measures the energy transferred to the water due to the combustion of a substance. Using a calorimeter yields an experimental value for the heat of combustion. Energy from the combustion reaction is transferred to the contents of the calorimeter and is observed as a temperature change to the water within the calorimeter.

 **calorimeter:** a device that measures energy changes

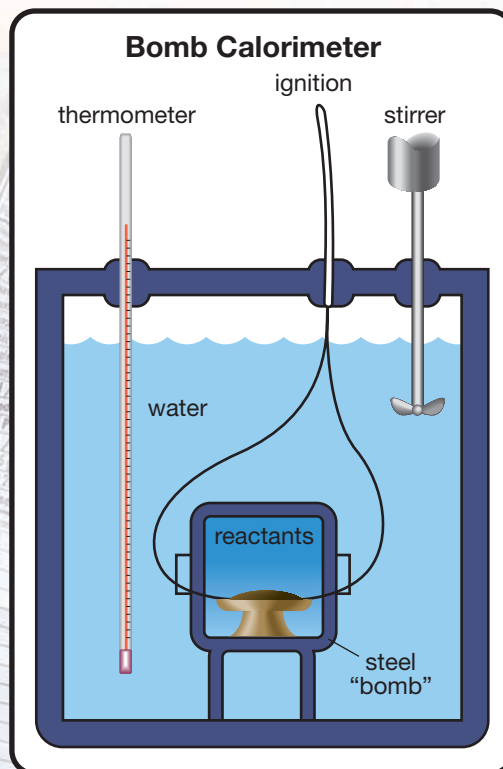
In the “Determining Heat of Combustion” investigation, you were probably able to indicate more than one flaw, most likely involving the probable loss of energy. Energy radiating away from the water cannot be measured using a calorimeter. Energy losses that occur with crude calorimeters decrease the accuracy of experimental values. Scientists performing

experiments use more advanced calorimeters that are better able to ensure that the energy released by the reaction is mostly, if not completely, transferred to the water. This ensures that more accurate changes in temperature are measured. In a bomb calorimeter, the combustion reaction occurs within a sealed chamber (bomb) submerged in the water. The water is contained in an outer double-walled container—similar to that of a Thermos bottle—designed to reduce the transfer of energy to the surroundings. These modifications to the basic design of a calorimeter minimize energy loss to the surroundings and improve the accuracy throughout the experiment.



DID YOU KNOW?

At one time, the values for energy in food were determined using a calorimeter. Now, values for energy are calculated using the mass of fat, carbohydrates, and protein within the food and the heat of combustion values for each gram of fat, carbohydrates, and protein.



Theoretical Heat of Combustion—Hess's Law

When determining heat of combustion, another approach is to consider the energy involved in the formation of the products and the reactants within a chemical system. Although it is impossible to exactly know the potential energy of any substance, the energy associated with a substance's formation—its **standard heats of formation**—can be used to estimate its chemical potential energy. As you have seen, the difference between the chemical potential energies of the products and the chemical potential energies of the reactants is equal to the energy change for the reaction.

The standard heat of formation for an element, when not part of a compound, is defined as zero. Each compound is given a standard heat of formation that is equal to the energy change that occurs during the chemical reaction in which the compound is formed. Giving elements an arbitrary value of zero allows for comparisons to be made among compounds and for an estimation of the potential energy of a compound (higher or lower than its respective elements). Using the standard heats of formation for all the substances involved in a reaction allows for a comparison of the potential energy of the products relative to the reactants. This is summarized in the formula for energy change of reaction, $\Delta_r H^\circ$.

standard heat of formation ($\Delta_f H^\circ$): the energy change for a chemical reaction that involves the formation of a compound from its elements determined at standard conditions

$$\Delta_r H^\circ = \sum n \Delta_f H^\circ \text{ products} - \sum n \Delta_f H^\circ \text{ reactants}$$

where $\Delta_r H^\circ$ = energy change of reaction (kJ)

\sum = the sum of

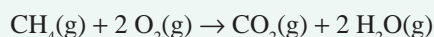
n = amount (number of moles) represented by coefficient from balanced chemical equation

$\Delta_f H^\circ$ = standard heat of formation

If the reaction is a combustion reaction, $\Delta_r H^\circ = \Delta_c H^\circ$. This means that the heat of combustion, $\Delta_c H^\circ$, is equal to the difference between the sum of the heats of formation of the products and the sum of the heats of formation of the reactants for that equation. Example Problem 1.1 shows how this formula can be applied to predicting the energy change for a chemical reaction.

Example Problem 1.1

The balanced chemical equation for the combustion of methane is as follows.



Use standard heats of formation to calculate the energy change for the combustion for methane, the main component of natural gas.

Solution

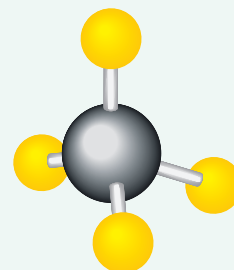
$$\Delta_c H^\circ = \sum n \Delta_f H^\circ \text{ products} - \sum n \Delta_f H^\circ \text{ reactants}$$

Organize the information in a table.

	Products		Reactants	
Substance	$\text{CO}_2(\text{g})$	$\text{H}_2\text{O}(\text{g})$	$\text{CH}_4(\text{g})$	$\text{O}_2(\text{g})$
Coefficient	1 mol	2 mol	1 mol	2 mol
$\Delta_f H^\circ$	−393.5 kJ/mol	−241.8 kJ/mol	−74.6 kJ/mol	0

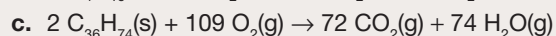
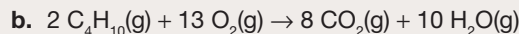
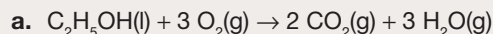
$$\begin{aligned} \Delta_c H^\circ &= \sum n \Delta_f H^\circ \text{ products} - \sum n \Delta_f H^\circ \text{ reactants} \\ &= \left[(1 \text{ mol}) (-393.5 \text{ kJ/mol}) + (2 \text{ mol}) (-241.8 \text{ kJ/mol}) \right] - \left[(1 \text{ mol}) (-74.6 \text{ kJ/mol}) + (2 \text{ mol}) (0) \right] \\ &= (-393.5 \text{ kJ} - 483.6 \text{ kJ}) - (-74.6 \text{ kJ} + 0) \\ &= -802.5 \text{ kJ} \end{aligned}$$

The energy change is −802.5 kJ.



Practice

22. The following balanced chemical equations are for the combustion reactions for each of the fuels tested in the “Determining Heat of Combustion” investigation. Calculate the heats of combustion for each reaction.



Note: Assume the heat of formation for paraffin wax, $\text{C}_{36}\text{H}_{74}(\text{s})$, is -1862.6 kJ/mol .

23. Express the heats of combustion in question 22 as energy changes per mole of fuel combusted. State a reason why energy changes are often expressed per mole of reactant.



DID YOU KNOW?

The formula $\Delta_r H^\circ = \sum n \Delta_f H^\circ \text{ products} - \sum n \Delta_f H^\circ \text{ reactants}$ can also be used to predict the energy change for any chemical reaction, as long as standard heats of formation for the products and reactants are provided. This formula is one way to state Hess’s Law, named after Germain Henri Hess—a Swiss chemist who, in 1840, published his work with energy changes in chemical reactions. Hess’s Law states that the energy change for a process is the same whether it occurs in one step or many steps. Energy diagrams are another way to summarize Hess’s contribution to a greater understanding of energy changes in chemical reactions.

Machines—Always Leaking Energy



Think back to the first time you ever checked a machine’s oil level. Checking fluid levels has become a standard part of most driver-training classes. At some point in the instructions of how to locate and read the oil level on the dipstick, instructors will also warn you that the engine will still be hot, even though it is not running. As with any engine that runs by burning fuel, the combustion of the fuel results in energy being transferred to the engine parts.

It’s important to remember that all the energy transferred to the engine is an important component of the total energy output of the engine. The total output energy of the engine is always equal to the total input energy of the engine. In other words, energy can neither be created or destroyed. In previous courses you may have referred to this as the law of conservation of energy. It is also called the **first law of thermodynamics**.

The flow of heat to parts of the engine is classified as non-useful output energy because it does not contribute to the useful work done by the engine. The engine is designed to exert a force on the moving parts that give the vehicle kinetic energy. Whenever energy does work, some of it is wasted. Some of it is lost to the surroundings in the form of heat. In the “Determining Heat of Combustion” investigation, you probably realized that not all of the thermal energy released by

the combustion reaction is transferred to the water. Some thermal energy escaped to the room at large. Even if you tried to capture 100% of that escaping energy, as is attempted with bomb calorimeters, you will never fully succeed. A tiny fraction of the energy always escapes. So, inevitably, when people harness energy to do work, some energy passes to the environment as waste heat. The **second law of thermodynamics** states that 100% efficiency is impossible. All people can do when designing machines is to try and minimize waste heat.

► **first law of thermodynamics:** a law stating that energy cannot be created or destroyed

Energy is always conserved.

► **second law of thermodynamics:** a law stating that when energy is transferred or changed from one form into another, some of the energy is always transferred to the surroundings (usually as waste heat)

Example Problem 1.2

During a trip, a car uses 2.35×10^7 kJ of chemical potential energy supplied by combustion of gasoline. The car's engine is able to transform 4.73×10^6 kJ of that chemical potential energy into useful work.

- Calculate the efficiency of the car.
- Use the first law of thermodynamics to determine the percentage of the car's input energy that is transformed into non-useful forms of output energy.
- List some of the non-useful forms of energy produced by the car's engine.
- Explain why the non-useful forms of output energy can never be completely eliminated.

Solution

a. useful output energy = 4.73×10^6 kJ

input energy = 2.35×10^7 kJ

energy efficiency = ?

$$\begin{aligned}\text{energy efficiency} &= \frac{\text{useful output energy}}{\text{input energy}} \times 100\% \\ &= \frac{4.73 \times 10^6 \text{ kJ}}{2.35 \times 10^7 \text{ kJ}} \times 100\% \\ &= 20.1\%\end{aligned}$$

The energy efficiency of the car is 20.1%.

- According to the first law of thermodynamics, energy is conserved; therefore, the total energy output equals the total energy input. Since 20.1% of the output energy does useful work, that means $100\% - 20.1\% = 79.9\%$ of the input energy is transformed into non-useful forms of energy.
- The non-useful forms of energy include the thermal energy that passes as waste heat to the environment, the radiant energy produced during combustion, and the sound energy produced by the car's engine.
- According to the second law of thermodynamics, it is impossible for a machine designed to do useful work to be 100% efficient because some energy is always lost in the transfer.



DID YOU KNOW?

Energy loss is at its greatest when objects are hot because the greater the temperature difference, the greater the rate of heat loss to the cooler surroundings.

Investigation

Calculating the Efficiency of a Calorimeter



Science Skills

✓ Analyzing and Interpreting

Purpose

In this investigation you will use the results from the "Determining Heat of Combustion" investigation and the heats of combustion calculated in Practice question 23 to calculate the energy efficiency of the calorimeter.

Pre-Lab Question

- For a calorimeter, define *useful output energy* and *input energy*. Describe how useful output energy is measured.

Procedure

step 1: Record the following table into your notebook.

Fuel	ethanol	butane	paraffin wax
Useful Output Energy (kJ/mol)			
Input Energy (kJ/mol)			
Energy Efficiency of Calorimeter (%)			

step 2: Insert your results from the "Determining Heat of Combustion" investigation into the first row of the table.

step 3: Insert your answers to Practice question 23 into the second row of the table.

Analysis

- Calculate the energy efficiencies of the calorimeter. Record these values in the third row of the table.
- Calculate an average efficiency of the calorimeter.
- List possible reasons why the energy efficiency of the calorimeter was less than 100%.
- State the precision (number of decimal places) of the balance used in the "Determining Heat of Combustion" investigation. Describe the effect the precision of the masses measured has on the values calculated for the efficiency of your calorimeter.

Coal-Fired Generating Stations

Coal is used to produce more than 70% of Alberta's electricity. Because of the increased price for petroleum, coal's popularity has increased as a source of energy to meet ever-increasing energy needs. A coal-fired generating station operates by burning coal, converting its chemical potential energy into electricity.

The process of transforming the energy within coal requires that it first be crushed into a fine dust and blown into a combustion chamber, where it ignites. The energy released by the combusting coal is then absorbed by water contained within a network of tubes surrounding the combustion chamber. The combustion chamber and water lines form the boiler, allowing the water in the lines to be converted into high-pressure steam. The force generated by the expansion of the high-pressure steam causes the turbine to spin. The axle of the turbine is connected to a generator, which is composed of a conductive wire spinning within a magnetic field. As you saw in Unit C, a generator induces an electrical current in the conducting wire—thus producing electricity. The following flowchart summarizes how the energy is transformed during the conversion of coal into electricity by the generating station.

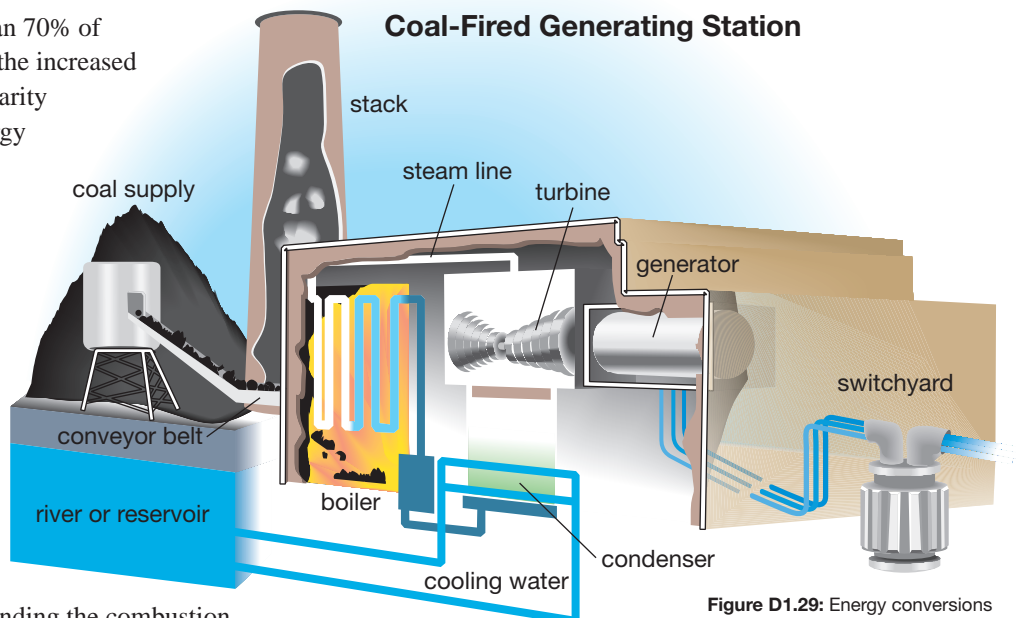
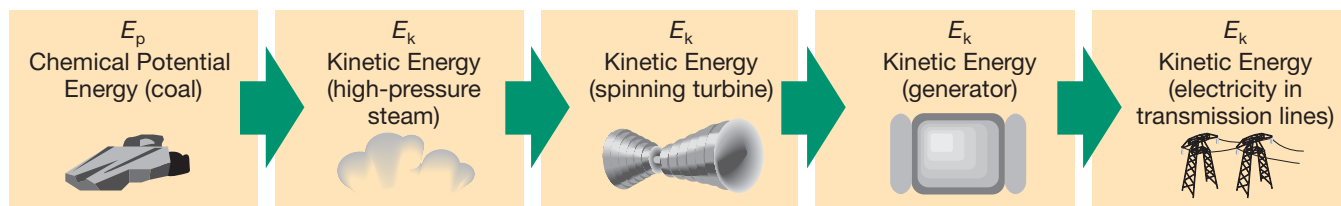


Figure D1.29: Energy conversions in a coal-fired generating station



Practice

- Electricity can be produced using natural gas—a fossil fuel—in place of coal. Use the Internet to research natural gas-fired electricity generation. Identify similarities and differences between coal-fired electricity generation and natural gas-fired generation in terms of processes used to produce electricity and the energy transformations involved.
- Modifications to the processes in a coal-fired power plant are listed in the following table. Explain how each modification could improve the energy efficiency of the plant.



Modification	Description
I	evaporating water normally found within coal prior to combustion
II	allowing the steam to pass more than once across turbine blades

Science Links

Older coal-fired generating stations are only about 33% efficient. Experimental, low-emission generating stations may improve energy efficiency to 45% or higher. More information about the processes involved in low-emission coal-fired power plants appears in Units B and C.

1.3 Summary

Fossil fuel combustion reactions provide the energy for many of the technological devices you use daily, like vehicles, electrical appliances, and electronic devices. The energy released by a combustion reaction can be measured experimentally or by using standard heats of formation. All energy conversions are less than 100% efficient. This is due to some of the energy being transferred to the environment as heat.



1.3 Questions

Knowledge

1. Identify the energy source used to generate the majority of Alberta's electricity.
2. Name the type of energy present within fossil fuels.
3. Identify the type of chemical reaction used to release the energy stored in fossil fuels.
4. Write the formula used to calculate energy change for a combustion reaction using standard heats of formation. Identify each variable in the formula.
5. Define *heat of combustion* and *standard heat of formation*.
10. For thousands of years, the Inuit traditionally relied upon animal power for transportation. In the 1970s, gasoline-powered snowmobiles replaced dogsleds as the primary mode of transportation for Inuit in the Arctic during the winter months.



Applying Concepts

6. Explain how the combustion of a hydrocarbon causes a change in potential energy.
7. Describe the result of a change in potential energy during a chemical reaction.
8. Draw an energy diagram for an exothermic process indicating the position of the reactants, products, and net energy change.
9. A natural gas-fired generating station uses 2.5 MJ of heat from the combustion of methane.
 - a. Calculate the station's energy efficiency if 1.3 MJ of electrical energy is generated.
 - b. Compare this to the typical efficiency of a coal-fired generating station.
11. For millennia, Inuit people have burned seal and whale blubber as sources of heat and light. Design an experiment that could compare the heat of combustion of seal blubber with that of whale blubber. Your design should include a problem statement; manipulated, responding, and controlled variables; a diagram of the apparatus you will use; and a data table showing the information you wish to measure and record.
 - a. Write the balanced combustion reaction for octane, $C_8H_{18}(l)$, the main component of gasoline.
 - b. Use standard heats of formation to calculate the heat of combustion for octane.